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TECHNICAL REPORT

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THE EFFECT OF LOADING RATE AND TEMPERATURE ON THE FRACTURE TOUGHNESS OF HIGH STRENGTH STEELS

BY

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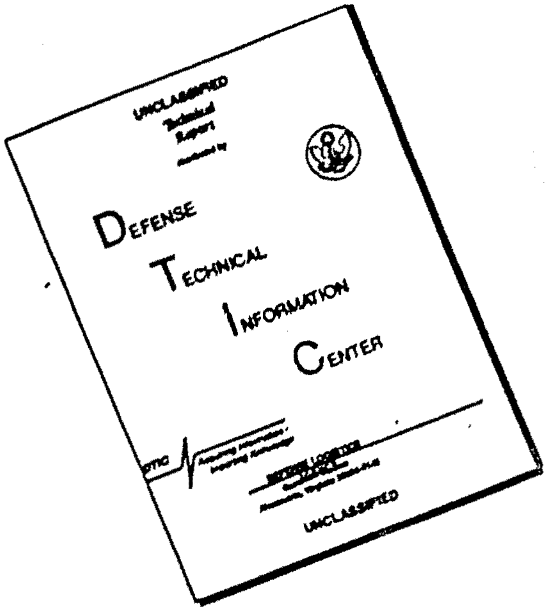

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THE EFFECT OF LOADING RATE AND TEMPERATURE
ON THE FRACTURE TOUGHNESS OF HIGH STRENGTH STEELS

ABSTRACT

The effect of loading rates, ranging from 10 to 10^5 ksi $\sqrt{in}$/sec, and temperatures, ranging from room temperature to -100°F, on the plane strain fracture toughness of several high strength alloy steels has been determined. Materials investigated are a commercial 4340 steel, a modified 4330 steel from a gun tube forging having three different heat treatments and two different heats of 250 grade maraging steel.

Test specimens utilized are essentially ASTM "compact tension" type specimens of one inch thickness. Tests were conducted on an open loop, hydraulic, high loading rate tensile testing machine.

Results are presented in the form of graphs of fracture toughness versus temperature for the maximum and minimum loading rates ("dynamic" and "static"). Fracture toughness versus loading rate at -60°F and yield strength versus elastic strain rate at room temperature, -60°F and -100°F for one heat of maraging steel are also reported.

Cross-Reference Data

Fracture Toughness

Strain Rate

Mechanical Properties

High Strength Steels

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The Author appreciates the assistance of W. M. Yaiser in conducting the experiments reported herein.

INTRODUCTION

During recent years the rapid development of fracture mechanics has made possible the accurate prediction of the fracture load for certain structures containing cracks or crack-like defects. This requires the calculation of a stress intensity factor which represents the intensity of the elastic stress singularity at the crack tip. If the stress state at the tip of the crack is one of plane strain, as in the case of thick-walled pressure vessels, a value of plane strain fracture toughness (K_{Ic}) for the material is required. This is the critical value of stress intensity at which fracture will initiate.

Considerable effort has been expended on the development of standard test methods for measuring K_{Ic}. This work has been coordinated by ASTM Committee E-24 and the test methods which have evolved are given in detail in Ref. 1. These test methods measure the K_{Ic} under quasi-static loading rates. In many cases the rate of load application in an actual structure may be several orders of magnitude faster than that used in the standard test. If the rise time of the load is of the same order of magnitude as the time for elastic stress wave propagation through the portion of the structure of interest, the loading is primarily by stress wave propagation and interaction. In this case the

quasi-static elastic calculation of the stress intensity factor is obviously not valid. This is true for many cases of impact or explosive loading.

There are, however, many cases in which the loading times are sufficiently long that the static elastic analysis will apply, but sufficiently short that strain rate effects on the behavior of the material may be significant. This is the region of interest in this paper.

Several investigators have studied the effect of loading rate on fracture toughness, but most of this work is on relatively low strength steels which are generally more rate sensitive with regard to yield strength. Also, some of these utilized specimen configurations and/or test methods which left some doubt as to whether they were actually measuring K_{Ic}. Of particular note is the work of Shoemaker(2), Krafft(3) and Bush(4). They found that the fracture toughness of high strength steels is not greatly rate sensitive. However, some indications of slight rate sensitivity under certain conditions were reported. These will be discussed later.

The materials used in this current study are a 4340 steel bar stock tested in the transverse and longitudinal direction, a modified 4330 steel from a large gun tube forging having three different heat treatments and two different heats of type 250 maraging steel. Test temperatures ranged from room temperature to -100°F.

The loading rates are expressed in terms of the average time rate of increase in stress intensity factor during the load application, $\dot{K}$.

A basic quasi-static rate of 10 ksi $\sqrt{in}$/sec and a basic dynamic rate of 10^5 ksi $\sqrt{in}$/sec were used for all materials. In addition, the maraging steel was tested at a series of intermediate rates at a selected temperature to determine the character of the variation of K_{Ic} with the loading rate.

PROCEDURE

The test specimen utilized in this study, as shown in Fig. 1, is essentially the "compact tension" specimen which has been standardized by ASTM Committee E-24[1]. The initial portion of this program was started before the final form of the ASTM standard specimen was adopted. As a result the earlier specimens varied slightly in that the pin hole diameter was 3/4 inch instead of 1/2 inch and the overall width was 2.75 inches instead of 2.50.

The measurement of K_{Ic} by the method of Ref. 1 requires that initial crack extension be detected by measuring the change in compliance of the specimen associated with a two percent increase in crack length. This is accomplished by obtaining a plot of crack opening displacement versus load and determining the load at the intersection of this curve with a secant offset line having a slope 4% less than that of the linear portion of the curve. In the initial part of this program the measurement of the crack opening displacement was accomplished by measuring the relative displacement of the clevises as shown in Fig. 2. A high frequency, variable impedance displacement transducer was used to indicate the change in the space between the

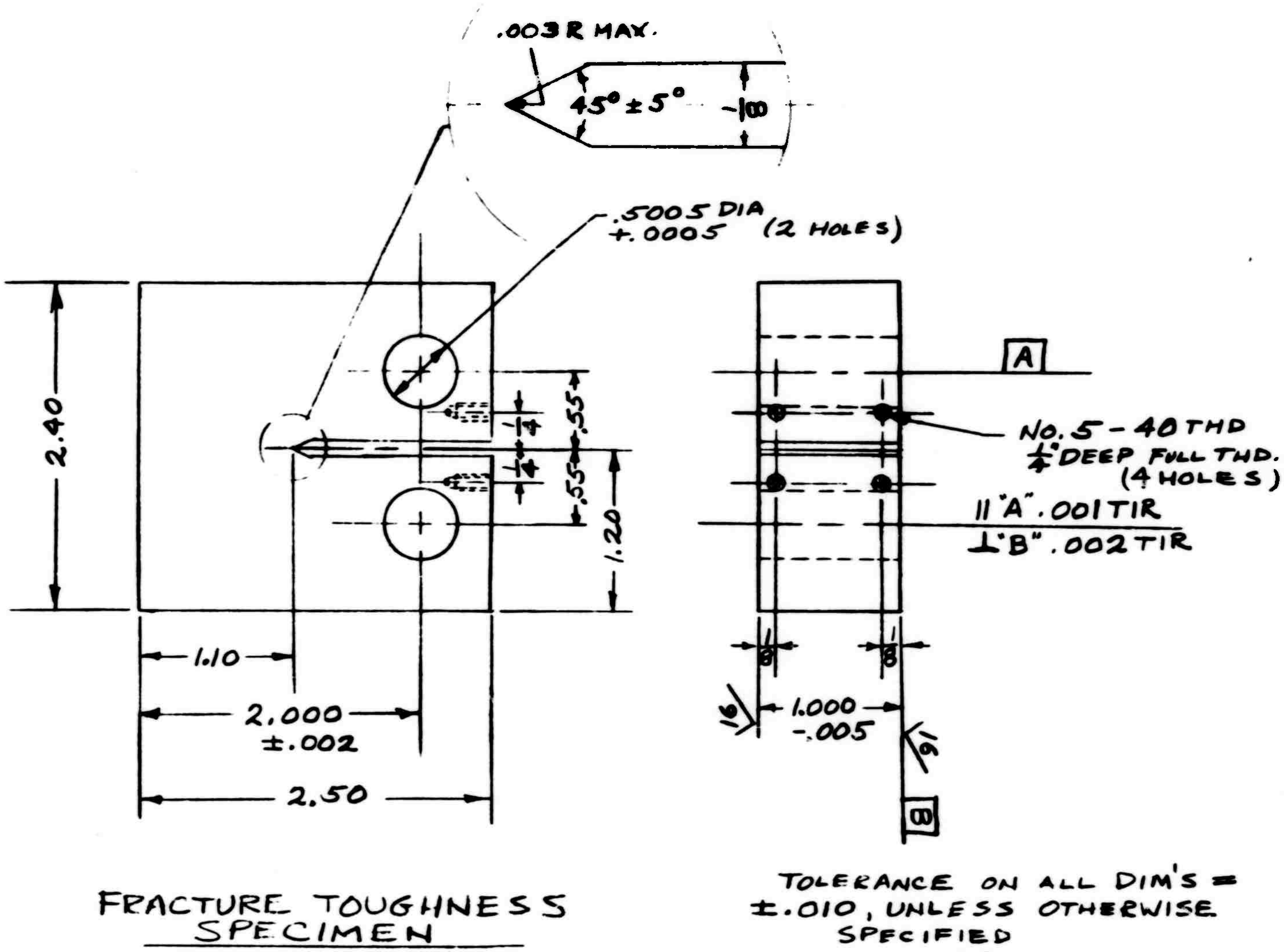


Figure 1. Test Specimen.

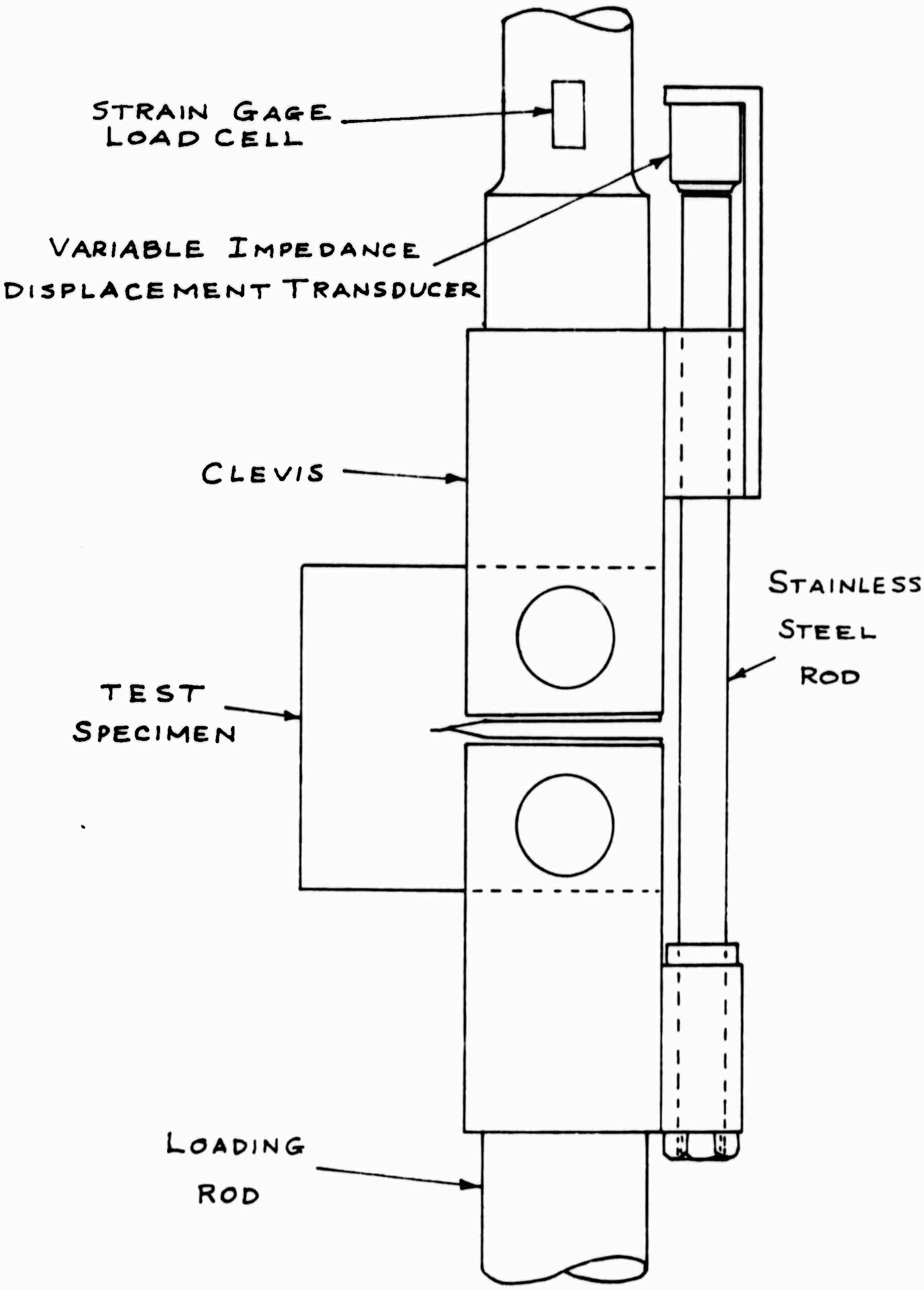


Figure 2. Test Set-up.

end of the stainless steel rod and the transducer. Neglecting inertial effects, this is equal to the relative displacement of the clevises. As long as the elastic deflections of the clevises and the loading pins are linear functions of the load, the output of the displacement transducer is a linear function of the crack opening displacement of the specimen. Any sudden departure from linearity will thus be detected and will truly represent the load at which crack extension occurs. If the deviation from linearity is gradual, there is some question as to whether the load at 4% secant offset, as measured by this method, truly represents two percent crack extension. Although the answer to this question could be determined, it was not, for the following reason. For all of the results reported in this paper which required the use of the secant offset method to determine the critical load, the value of K associated with this load was sufficiently high that the specimen size was too small to meet the ASTM size requirements. Therefore, the results of these tests cannot be designated as K_{Ic} values as defined by ASTM. It is customary at this time to designate such results as "K_Q" and consider them only relative values of toughness.

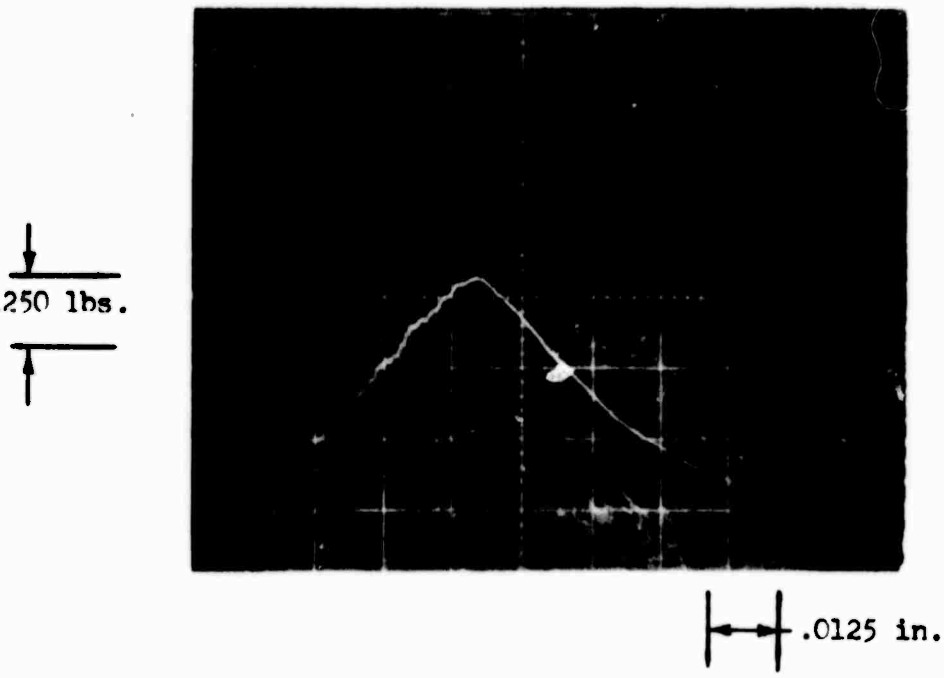
The later results reported herein (namely, heat no. 2 of the 250 maraging steel and some of the 4340 data) were obtained using a specimen configuration and displacement measuring system which complies with all of the requirements of Ref. 1. The displacement transducer was bolted directly to the specimen.

As shown in Fig. 2 the load on the specimen is measured by a strain gage load cell which is calibrated on a standard tensile testing machine at both room temperature and with the specimen cooled to -100°F. Any variation of load cell calibration with temperature was found to be less than 0.5%. The maximum total error in the measurement of the peak loads is estimated to be less than 2%.

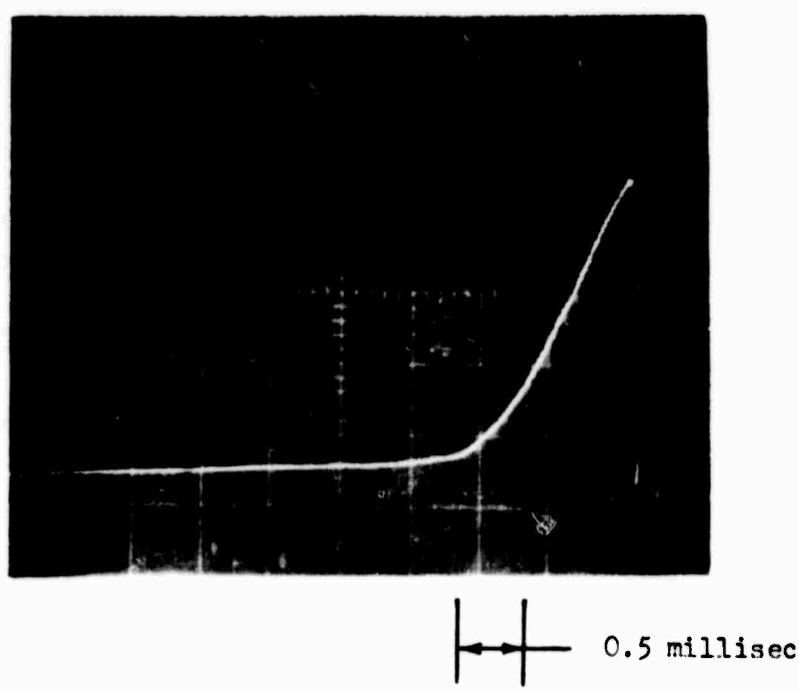
The testing machine used for all of the tests reported has been described in a previous paper(5). It is based on energy storage in a liquid (water) charged accumulator and rapid fluid transfer to a piston and cylinder loading frame through a quick-opening valve. An adjustable throttle valve in the line between the quick-opening valve and the loading cylinder is used to control the loading rate.

The outputs of the load cell and displacement transducer are connected to a high frequency response, light beam oscillograph to provide load-time and displacement-time records. They are also connected to the axes of an X-Y storage oscilloscope to provide a load-displacement plot directly. Typical load-displacement plots are shown in Fig. 3 along with a typical load-time trace for a dynamic test. This was recorded on an oscilloscope instead of the light beam oscillograph for ease of reproduction.

In the low temperature tests the specimen was surrounded by a container filled with a mixture of dry ice and alcohol at the desired test temperature.



LOAD-DISPLACEMENT TRACE



LOAD-TIME TRACE

Figure 3. Typical Data Traces.

MATERIALS

The materials utilized in this study were commercial 4340 steel, 4330 modified steel and 250 grade, 18% nickel, maraging steel. The chemical composition of these materials is shown in Table I. The heat treatment and resulting tensile properties are shown in Table II.

The 4340 steel was obtained in the form of 1 x 3 inch rolled bar stock. It was cut into blanks about 2½ inches long and heat treated as shown in Table II. The blanks were then machined into test specimens so that the loading direction (normal to the crack surface) coincided with either the longitudinal or transverse direction. They were then fatigue pre-cracked on a Sonntag fatigue machine using a 5:1 load magnification fixture. The fatigue stress intensity during the final .050 inches of fatigue crack propagation did not exceed 15 ksi $\sqrt{in}$ for the transverse specimens or 21 ksi $\sqrt{in}$ for the longitudinal specimens.

The 4330 modified material is a vacuum arc remelted steel taken from a large gun tube forging 15½ inches outside diameter, 6½ inches inside diameter and about 35 feet long. This material was tested in three different conditions. The heat treatment associated with each condition is shown in Table II. That shown for the as-received material is the heat treatment given the entire forging by the supplier. The oil quenched and salt quenched material was cut into specimen sized blanks prior to heat treatment. The resulting microstructures are shown in Fig. 4. All specimens of this material were cut from the forging so that the crack front was parallel to the axis of the tube

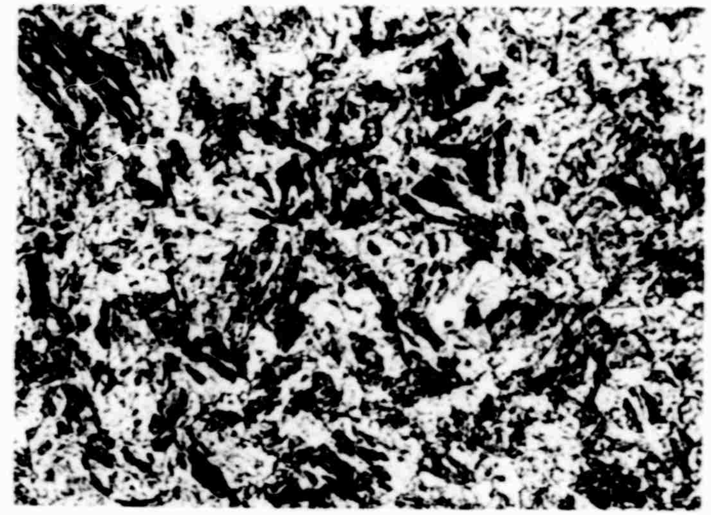
TABLE I. CHEMICAL COMPOSITIONS
Weight Percent

MATERIAL	C	S	P	Mn	Si	Ni	Cr	Mo	V	Co	Ti	Zr	B	Al
4340	0.38	.011	.010	0.74	0.32	1.97	0.77	0.27	—	—	—	—	—	—
Mod. 4330	0.34	.011	.012	0.50	0.22	3.08	1.15	0.58	0.13	—	—	—	—	—
Maraging 250, Ht 1	0.01	.005	.004	0.03	0.07	18.40	—	4.72	—	7.60	0.40	0.014	0.004	0.07
" " Ht 2	0.009	.002	.005	0.02	0.02	18.90	—	4.90	—	8.05	0.44	TRACE		0.09

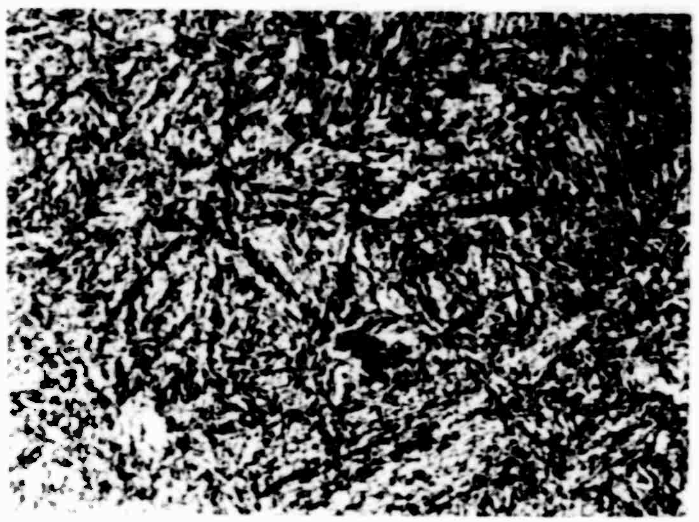
TABLE II. HEAT TREATMENT AND TENSILE PROPERTIES

MATERIAL	HEAT TREATMENT			TENSILE PROPERTIES (.357 Dia. Specimens)		
	AUSTENITIZE	QUENCH	TEMPER	YIELD STRENGTH ksi	TENSILE STRENGTH ksi	%R.A.
4340 (Long.)	1550°F	Oil	900°F, 1 hr.	185	194	53
Mod. 4330 As Rec'd	1560°F	Water	950°F, 10 hrs.	185	200	45
Oil Quench	1550°F	Oil	1050°F, 4 hrs.	181	193	54
Salt Quench	1550°F	Salt @ 600°F	1050°F, 4 hrs.	157	181	51
Maraging 250, Ht 1		Age 900°F, 4 hrs.		228	244	43
Maraging 250, Ht 2		Age 900°F, 4 hrs.		260	270	27

OIL QUENCHED, 2000X



SALT QUENCHED, 2000X



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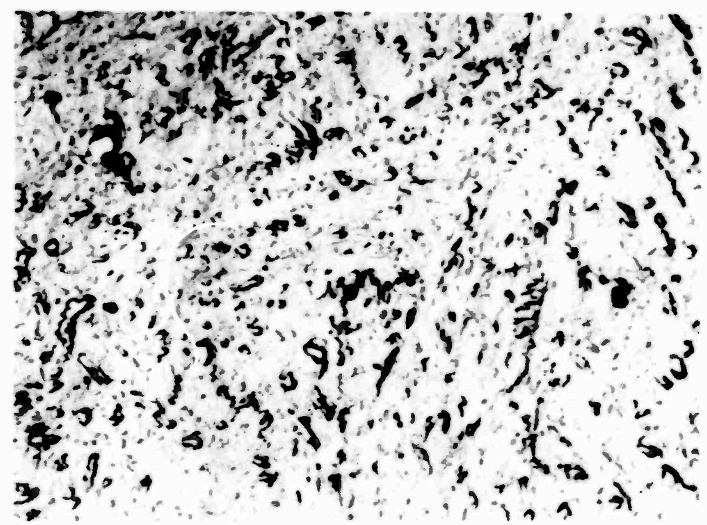

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Figure 4. Microstructures of Modified 4330 Material.

and the loading direction was the tangential direction in the tube. They were fatigue pre-cracked as before at a final fatigue stress intensity of less than 15 ksi $\sqrt{in.}$

The maraging steels tested were from two different heats of 250 grade, 18% nickel maraging steel. Both materials were purchased in the form of 6 inch square forged billets in the solution annealed condition. Heat no. 1 is a consumable vacuum melted material purchased in 1965. Heat no. 2 is a double vacuum melted material purchased in 1968. Specimens of both materials were cut from the billet so that the loading direction corresponds to the transverse direction in the billet. They were finish machined in the solution annealed condition and then aged at 900°F for 4 hours. They were then fatigue pre-cracked as before with the final fatigue stress intensity of 20 to 22 ksi $\sqrt{in.}$ This resulted in a final crack growth rate of 3 to 4 microinches/cycle in the heat no. 2 material.

RESULTS AND DISCUSSIONS

The results for the 4340 steel are shown in Fig. 5 as a plot of K_{Ic} or K_Q versus test temperature. The highly anisotropic nature of the toughness of this rolled material is evident from the difference between the longitudinal and transverse toughness. Most of these results were obtained in the early phases of the program using the non-standard specimen and test method. However, the results at -100°F and -40°F were obtained using the revised specimen and procedure which conforms to all requirements of Ref. 1 except the loading rate.

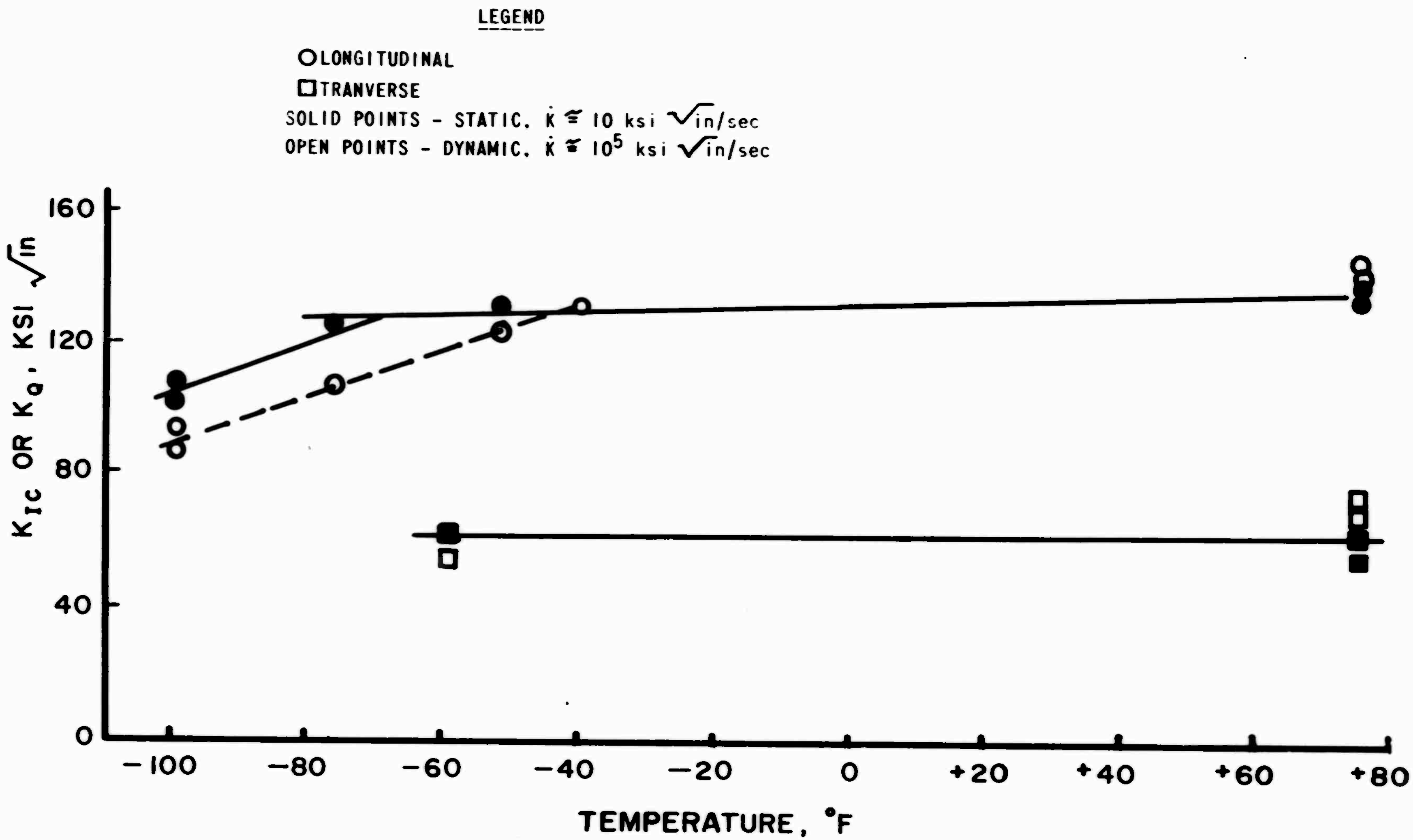

Figure 5. Fracture Toughness Versus Test Temperature for 4340 Steel.

The results for the transverse specimens show no significant effect of either temperature or strain rate in the range of temperature shown above -60°F. It is possible that this material may exhibit a transitional behavior at lower temperatures.

The longitudinal specimens are also essentially rate and temperature insensitive at temperatures above -50°F. However, at lower temperatures a toughness transition is seen in both the static and dynamic results. The transition temperature for the dynamic toughness is about 20° higher than that for the static values. These results are similar in form to the behavior of mild and low alloy steels reported by other investigators(2)(4). However, such materials show a much steeper transition and a greater difference between static and dynamic transition temperatures.

All of the data shown in Fig. 5 meet the ASTM size requirement except the longitudinal results at room temperature.

The results for the 4330 modified steel are shown in Fig. 6. All of the data shown, which exceed 120 ksi $\sqrt{in}$, do not meet the ASTM size requirement and thus must be considered as K_Q values. The oil quenched material (tempered martensite) appears to behave essentially the same as the 4340 steel, as would be expected. There is a slight increase in static K_Q with decreasing temperature. This is believed to be due to the increase in yield strength. It also appears that if this material exhibits a fracture toughness transition behavior, it occurs at a lower temperature than that for the 4340 steel and below -100°F.

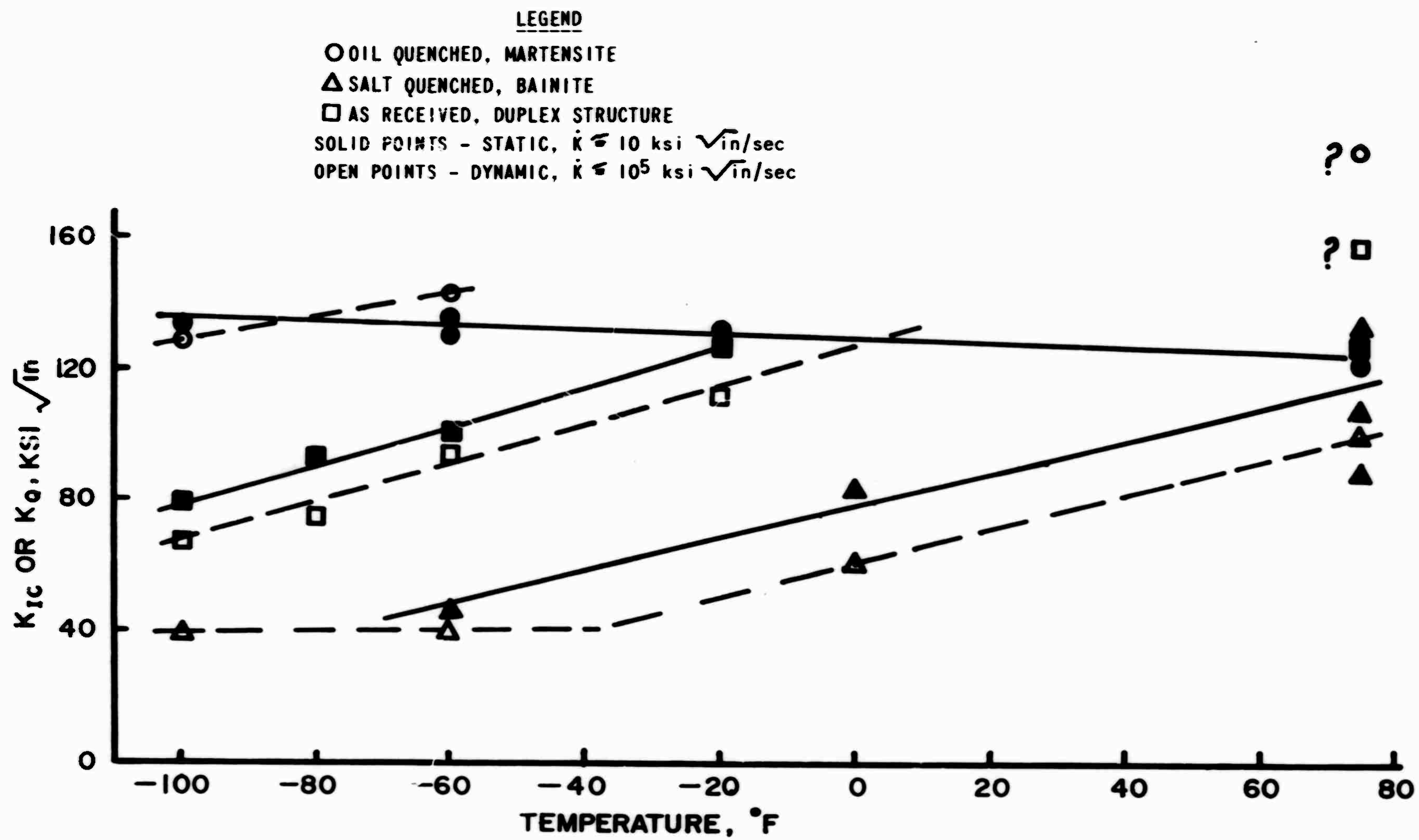

Figure 6. Fracture Toughness Versus Test Temperature for 4330 Modified Steel.

The two data points shown for the dynamic K_Q at room temperature for the oil quenched and as-received materials are marked with question marks. These are clearly invalid tests both due to size requirements and due to errors in obtaining the load at 4% secant offset previously discussed. The points are shown only to indicate the possibility of a rate sensitivity in these materials at this temperature. This tends to be confirmed by the fracture appearance data. The percentages of oblique fracture for the dynamic tests are 34% for the as-received, and 37% for the oil quenched material compared with 21% and 25% respectively for the static tests. Confirmation of the indicated rate sensitivity would require testing of larger specimens which is beyond the capability of the existing equipment.

The heat treatment given the salt quenched material resulted in a mixed structure of upper and lower bainite with possibly some martensite. This was intended to represent a "worst-case" structure which could be obtained by improper heat treatment of this material. The poor toughness behavior of this material is evident from Fig. 6 with a large decrease in toughness with decreasing temperature. The mid-point transition temperature for the dynamic tests is about 35°F higher than that for the static tests.

The microstructure of the as-received material is that which resulted from the heat treatment given the entire forging. It is mostly martensite but contains a small amount of bainite which results in the inferior toughness behavior of this material at low temperatures. This effect is discussed in detail in Ref. 6.

The fracture toughness results for this material, as shown in Fig. 6, are between those for the martensite and the bainite. They also show a transitional type of behavior but with a lower transition temperature than the bainite. The dynamic transition temperature is again slightly higher than the static value.

The results showing the variation of K_{Ic} with temperature for the maraging steel are plotted in Fig. 7. The results of both heats are shown and the similar behavior is evident. Heat no. 1 had a higher fracture toughness which might be expected since the yield strength of this heat is significantly lower than that of heat no. 2 as shown in Table II.

The static results show a continuous linear decrease in K_{Ic} with decreasing temperature. This is consistent with the results of Shoemaker and Rolfe[2]. The dynamic values are generally the same as the static values except at temperatures near -60°F. At this temperature both heats show a slight dip in the dynamic K_{Ic} values.

In order to further investigate this apparent rate sensitivity, which has not been previously reported for this material, a series of tests at varying strain rates were conducted at -60°F. These results are shown in Fig. 8. A generally linear decrease in toughness with increasing logarithmic loading rate is shown. This decrease is slight and it could be argued that it may be due to a systematic experimental error. However, since such a rate sensitivity was not seen at temperatures above and below -60°F under identical test conditions, it is believed to be a real effect.

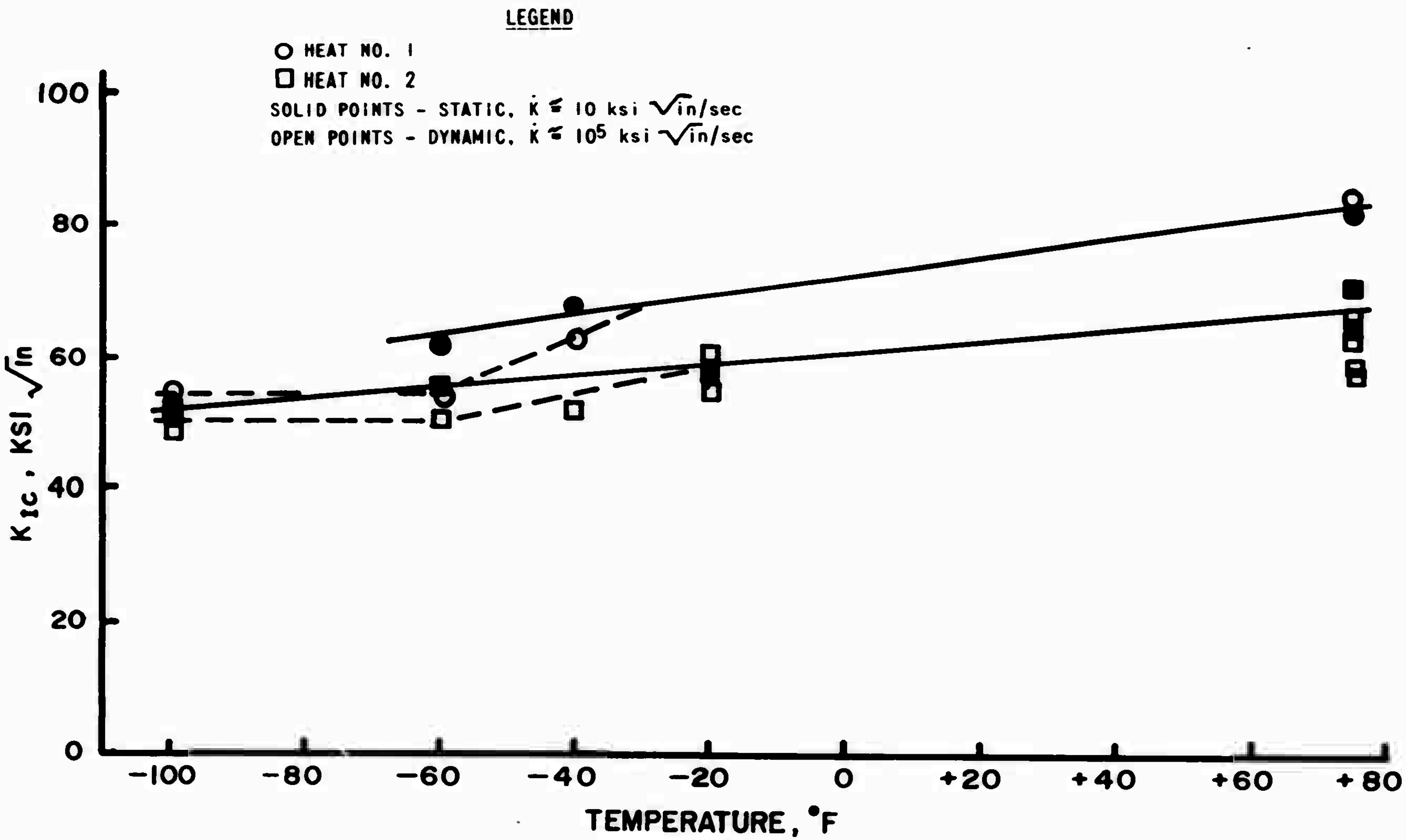

Figure 7. Fracture Toughness Versus Test Temperature for Maraging 250 Steel.

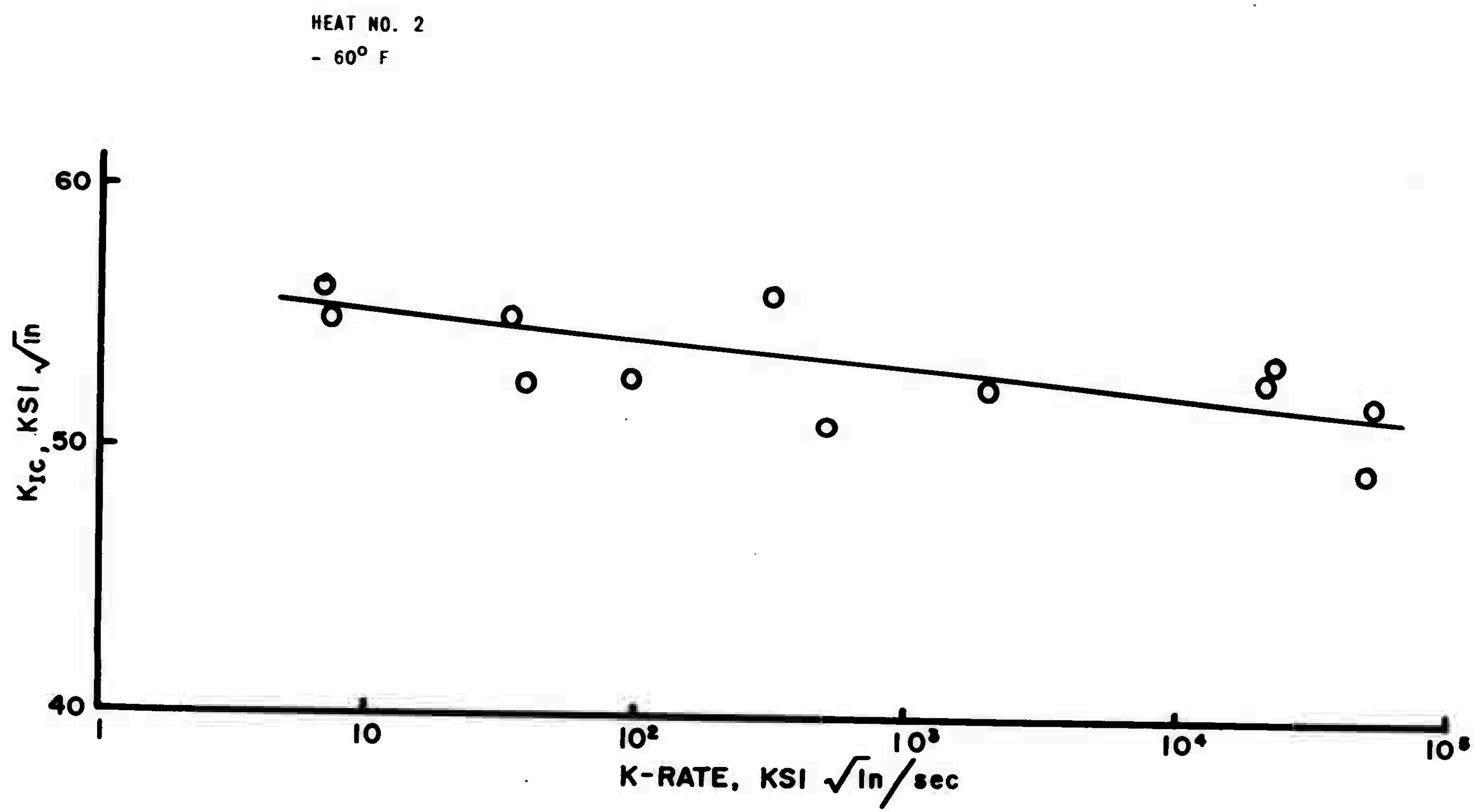

Figure 8. Fracture Toughness Versus Loading Rate for Maraging 250 Steel at -60°F.

Although this phenomenon is not of sufficient magnitude to be of any practical significance, it may be of interest to those concerned with the mechanisms of crack related fracture. In order to possibly relate this phenomenon to tensile behavior of this material, a series of tensile tests were conducted at several temperatures and strain rates. These results are shown in Fig. 9. The linear increase in yield strength with logarithmic strain rate is consistent with previously reported results. However, the amount of strength increase is less than that previously reported for 300 grade maraging steel[5]. In these tensile tests the specimen strain was measured with strain gages bonded directly to the specimen. Good stress-strain curves were obtained up to the tensile instability point.

Aside from the yield strength results shown, other data were taken from these tensile tests. These data were ultimate tensile strength, strain hardening exponent, and reduction of area of the necked region. Due to the small amount of plastic strain which occurs in this material prior to tensile instability, an accurate value of strain hardening exponent is difficult to obtain. The stress-strain data from the oscilloscope traces for several specimens were re-plotted as logarithmic true stress-true strain plots. The slope of the plastic region varied between 0.12 and 0.06 depending on the range of strain over which the slope is averaged. However, the strain at tensile instability was between 0.020 and 0.025 for all specimens. If this material followed the exponential strain hardening law, the strain at instability and the slope of the logarithmic stress-strain plot should be the same. The

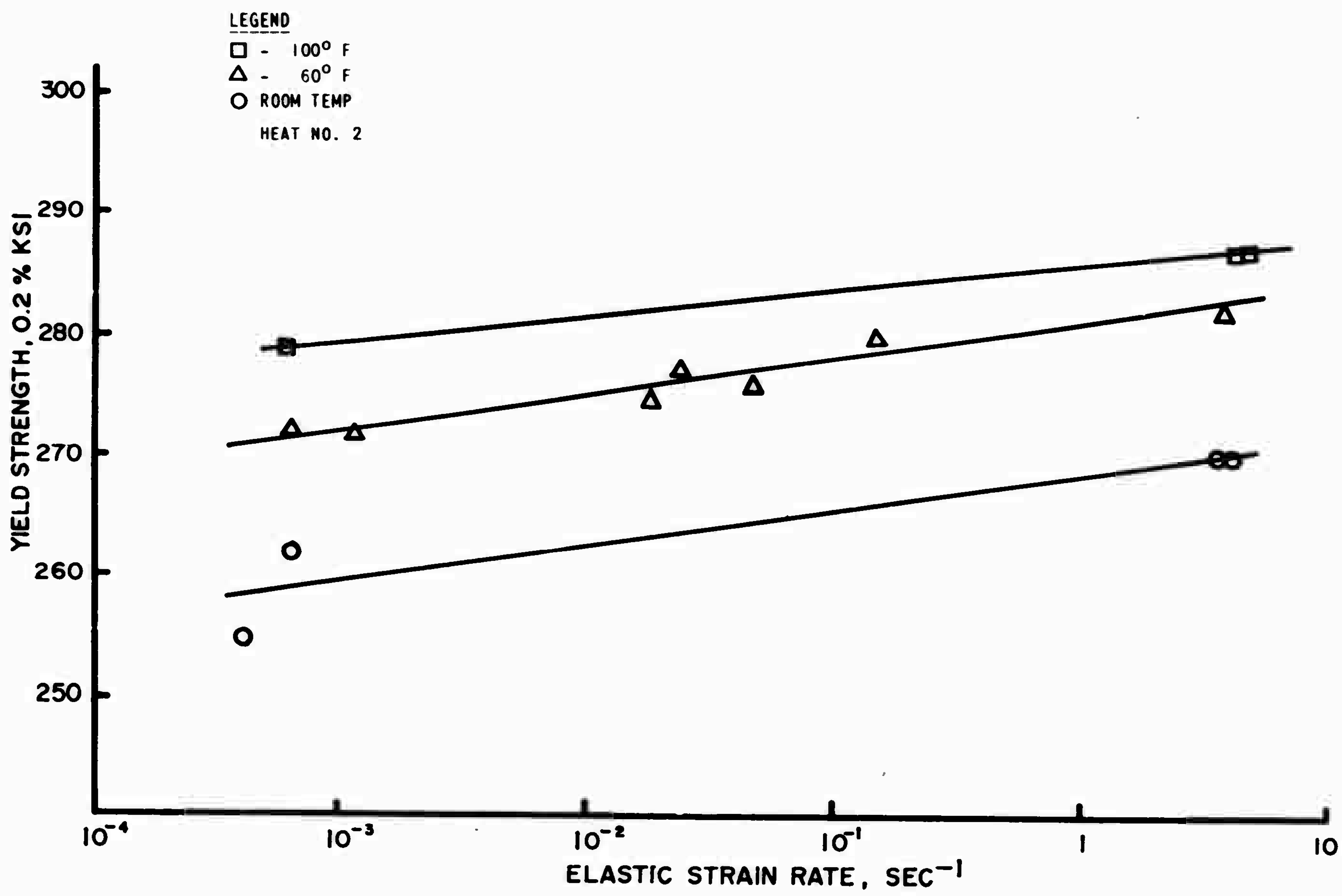

Figure 9. Yield Strength Versus Strain Rate for Maraging 250 Steel.

difference in these values indicates that this material does not behave according to the exponential strain hardening law except possibly over a very small range of strain values.

The reduction of area for all specimens varied between 26 and 33 percent and the difference between yield strength and tensile strength varied between 10,000 and 12,000 psi. There was no systematic variation of any of the above variables with either temperature or strain rate over the ranges investigated.

CONCLUSIONS

1. The plane strain fracture toughness of martensitic, 4340 steel is independent of both loading rate and temperature at temperatures above -50°F. At lower temperatures a decrease in toughness with decreasing temperature is found with the dynamic transition temperature about 30°F higher than the static value.

2. The fracture toughness of a modified 4330 steel (increased Ni, Cr, Mo and V) at low temperatures varies greatly with microstructure. The martensitic structure shows no significant variation in either static or dynamic K_{Ic} down to -100°F. The bainitic structure shows a considerable decrease in toughness between room temperature and -60°F with the dynamic transition temperature about 35° higher than the static. A duplex (martensite plus bainite) structure shows a similar transition behavior but with transition temperatures about 100°F lower than those for the bainite.

3. Maraging 250 steel shows a continuous decrease in K_{Ic} with decreasing temperature with no appreciable rate sensitivity except

at $-60^{\circ}F$ where a slight decrease in toughness with increasing loading rate is seen. This effect could not be correlated with any rate sensitive tensile property such as strain hardening or ductility.

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13. ABSTRACT

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High Strength Steels

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THE EFFECT OF LOADING RATE AND TEMPERATURE ON THE FRACTURE TOUGHNESS OF HIGH STRENGTH STEELS by David P. Kendall

Report No. WVT-7044, July 1970, 30 pages, 9 figures and 2 tables. AMCMS No. 501A.11.84400.02, DA Project No. 1T061101A91A. Unclassified Report

The effect of loading rates, ranging from 10 to 10^5 ksi $\sqrt{in}$/sec, and temperatures, ranging from room temperature to -100°F, on the plane strain fracture toughness of several high strength alloy steels has been determined. Materials investigated are a commercial 4340 steel, a modified 4330 steel from a gun tube forging having three different heat treatments and two different heats of 250 grade maraging steel.
Test specimens utilized are essentially ASTM "compact tension" type specimens of one inch thickness. Tests were conducted on an open loop, hydraulic, high loading rate tensile testing machine.

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